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A SEQUENTIAL DETECTION SYSTEM FOR THE PROCESSING OF RADAR RETURNS

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LEXINGTON MASSACHUSETTS

A SEQUENTIAL DETECTION SYSTEM FOR THE PROCESSING OF RADAR RETURNS

Summary - This paper describes a system which permits a substantial reduction in the amount of equipment required for the detection of narrow-band radar returns which may fall into any part of a wide, noisy Doppler band. The system utilizes a two-step process; the first providing a coarse, high-false-alarm indication of range and Doppler, and the second providing high quality detection and parameter estimation.

The basic principles are discussed, followed by a description of an experimental prototype system.

Experimental results are presented.

I. INTRODUCTION

When no *a priori* knowledge is available about the Doppler frequency or time of occurence of a narrow band return falling in a wide band noisy spectrum (see Fig. 1), an optimum method for real-time detection is to survey the spectrum with a parallel bank of a large number of matched filters arranged as a comb in frequency, and to observe whether the output of one or more filters exceeds a preset threshold. In order to be sure that at least one of the filters in the comb is approximately matched to the return, a sufficient number of the filters must be used to guarantee that one will be excited near its center frequency. The number of filters required to do this for a single receiver can get into the thousands.

For an example, consider a radar with a one-millisecond pulse, operating at 9,000 Mcps, and equipped to handle a range of target velocities of ± 18,000 miles per hour. A comb set of matched filters for this radar would contain approximately 2,000 filters.

In recent years, the problem of providing matched filtering for radars has become increasingly difficult because of the tendency for advanced radars to: (a) operate at higher carrier frequencies, which results in a larger Doppler band for a given range of target velocities; (b) be designed to handle a larger range of target velocities; (c) use long-duration, narrow-band signals to achieve high energy per pulse; and (d) have multiple simultaneous beams, each of which must be optimally processed.

Because of the increased cost per incremental db of system sensitivity in advanced radars, it is essential to use a processing system which provides as close to optimum signal detectability as is technically feasible.

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II. DETECTION TECHNIQUES

Detector Plus Video Filter

The simplest method for achieving reasonably high detectability on a simple pulsed return in noise is to feed the IF output into a diode detector whose output then feeds a video low-pass filter, matched (or nearly matched) to the envelope of the return (see Fig. 2). At high IF input signal-to-noise ratios, the detector plus video filter very nearly approximates an I.F. coherent matched filter which has been centered on the frequency of the return. When the input signal-to-noise ratio is reduced, the efficiency of the detector begins to fall off, and at an input signal-to-noise ratio of about plus three db the rate of signal degradation approaches a point below which the use of this technique becomes questionable. No information on the Doppler of the signal can be obtained during this process since this information is destroyed by the initial detection.

Medium-Bandwidth Filters Plus Detectors Plus Video Filters

The inability of the detector-plus-video-filter combination to function properly at low signal-to-noise ratios can be circumvented by using it in a filter system which guarantees that, for signals of interest, the detector will always be presented with a high signal-to-noise ratio. A comb set of medium-bandwidth pre-detection filters (IF filters whose bandwidths are large when compared to the signal spectral width, but small when compared to the total Doppler coverage band) raises the input signal-to-noise ratio to a value at which the detectors can efficiently operate. It is then possible to perform the remainder of the narrow banding with the use of a simple set of video filters as shown in Fig. 3.

An incidental benefit to the use of this technique is that it is possible to get an approximate indication of the Doppler of the signal, as will be shown later in this paper.

Bank of Narrow-Band Filters

A filtering technique that is able to achieve good performance at low input signal-to-noise ratios is that shown in Fig. 4; a comb set of IF coherent matched (or nearly matched) filters. It should be noted, however, that this method requires a considerably larger number of filter channels than does the technique described in the preceeding paragraph for the same total Doppler band.

Millstone Hill[1] Detection Technique

The Millstone Hill radar represents an early example of a radar in which the occurrence of a wide Doppler band and a narrow signal spectrum combine to cause a somewhat difficult problem in the processing of the receiver data.

The following is a list of the parameters of the Millstone Hill radar which, in part, determine the parameters of the detection equipment:

Operating Frequency:	440 megacycles per second
Type of Modulation :	Rectangular pulse, non-coded
Repetition Rate :	30 pulses per second
Pulse width (τ) :	2 milliseconds
$1/\tau$:	500 cps
Range of target velocities:	± 18,000 nautical miles per hour
Corresponding Doppler band	± 25 kcps

The matched filter for Millstone's two-millisecond pulsed sinusoid is a filter with the familiar $\frac{\sin x}{x}$ selectivity characteristic, centered at the frequency of the target return, with a ± 500 cps first null. In order to provide matched filtering over the entire 50 kcps of Doppler, a large set of $\frac{\sin x}{x}$ filters could be arranged as a comb in frequency as shown in Fig. 4. Based on the Millstone parameters, the matched filters could be spaced by 250 cps at the cost of a one db loss in signal detectability if the return falls midway between two filters. If this spacing is chosen, a total of 200 filters are required per receiver polarization in order to obtain full coverage in Doppler. Although this number of filters is not unreasonable if one uses a simple filter, the amount of equipment becomes prohibitive if one considers using this number of matched filters, each of which is highly complex. In order to permit a system which is feasible from an equipment standpoint, some deviation from the optimum filter must be allowed.

A small deviation (less than one db) from the optimum filter is allowed in the Millstone Hill detection equipment by the use of a single-tuned approximation. These filters are simple and relatively inexpensive, but a large number of them are still required in order to guarantee that one will be excited near its center frequency for any signal frequency.

Although a spacing on the order of 250 cps could be used between the filters at Millstone, it was decided to reduce this spacing to 160 cps for two reasons; to reduce the peak signal loss which occurs in the mid-range between two filters, and to provide a better indication of where in frequency the return fell, without requiring the additional complexity of frequency interpolation equipment.

Figure 5 shows the peak CW response and the response at the end of a two millisecond pulsed input for two adjacent Millstone filters. It should be noted that although the CW filter response has a half power bandwidth of 200 cps (the optimum single-tuned bandwidth for processing a two-millisecond pulsed sinusoid in noise) the pulse response characteristic exhibits an effective bandwidth greater than 450 cps.

Figure 6 shows part of Millstone's 628-filter (314 filters per receiver polarization) comb set and some associated digital encoding equipment.

Although the Millstone filtering technique offers conceptual simplicity (an important factor in the consideration of equipment which might be used in a production-model field radar, to be maintained by relatively untrained operating personnel) a rather large amount of equipment is required for its implementation. Certainly, if the Doppler band were a few times larger or the signal bandwidth a few times narrower, this technique would have to be abandoned.

III. SEQUENTIAL DETECTION AND PROCESSING TECHNIQUE

It was found that considerable economy could be realized by a two-step detection process; i.e., by first performing the job of detection in a coarse, high-false-alarm manner and then taking the stored IF input and routing it to a small comb set of narrow-band filters covering a bandwidth only as large as that required to find the signal with the aid of the original coarse measurements. Fig. 7 shows a block diagram of this sequential technique. When the output of the coarse detection equipment exceeds the first threshold, it initiates a selection of one of a bank of crystal oscillators. At the same time it gates the stored IF output into a converter which is fed by the selected local oscillator, thus sending the converter signal for test to the fine detection equipment. If the output of the fine detector does not exceed the second threshold, the original coarse detection is assumed to have been a false alarm and it is neglected. If the threshold is exceeded, a legitimate hit is assumed to have occurred and precision parameter-estimation equipment is then put into action.

In addition to using the knowledge of Doppler, gained in the first step of the detection process, it is also possible to utilize the coarse range measurement. Instead of allowing the fine narrow band filters to be fed with IF noise at all times (even when the signal is not present) the delayed signal can be gated into the fine filters using a gating signal which encloses the delayed IF signal. This noise-gating process reduces the contribution of the pre-signal noise to the total output noise. The experimental sequential processor, to be described later, utilizes this technique.

Coarse-Detection Equipment

The practicability of the sequential approach depends rather strongly on the availability of a simple device for performing the job of coarse detection. That is, there must be available a simple piece of equipment which can operate over the entire Doppler band with a probability of detection very nearly the same as a set of matched filters, at the price of a high false alarm rate. At the same time, the equipment must be able to give a coarse indication of the Doppler frequency and the range of the return for use in the second step of the detection process.

For a simple, rectangular, pulsed-sinusoidal signal this can be done as shown in Fig. 8.

The equipment primarily consists of a set of the filters shown in Fig. 3. The outputs of the video low-pass filters feed a set of diodes all of which have a common load. The output of this diode load then consists of the instantaneous maximum of the output of any one of the video filters. The voltage out of the diode network then feeds a range estimator which produces a trigger at the trailing edge of the return. This trigger is fed into the "sample" input of the "greatest of" comparator, which determines which of the inputs has the highest instantaneous voltage value. When the sample-pulse is removed, the output corresponding to the highest input stores a positive DC voltage, which is used to select a local oscillator for use in the conversion of the signal frequency into the band covered by the fine-detection filters.

Based on the Millstone Hill parameters it is possible to do the complete job of coarse Doppler and range estimation with about one five-inch subrack of transistorized equipment.

Fine-Detection Equipment

The fine-detection equipment primarily consists of a set of the filters shown in Fig. 4. The outputs of the narrow band filters are handled in much the same way as were the filters in the coarse detection equipment, except that the filter outputs also drive an interpolator.

The stability requirements on the center frequencies, bandwidths, and insertion losses of the narrow band filters are very stringent since in this system these stabilities, in conjunction with the operation of the interpolator, determine the basic limits of the no-noise Doppler accuracy.

Two of the blocks in Fig. 9 are not self explanatory and deserve further discussion; the Doppler interpolator, and the range estimator.

Doppler Interpolator

The Doppler interpolator is a device which reduces the Doppler measurement quantum to a value below that which would be obtained by encoding only the fact that the signal fell in a particular filter. As

shown in Fig. 10 it is a partially analog, partially digital device. A set of selector switches, controlled by signals from the fine "greatest of" comparator and range estimator, cause a gating into some analog circuitry of the peak voltage output of the two filters (labeled A and B) adjacent to the maximally excited one. This circuitry produces a trigger at a time proportional to the ratio of the amplitude out of filter A to the amplitude out of filter A plus filter B. The time between this generated trigger and the time of application of the two input voltages can be shown to be proportional to the frequency difference between some known frequency in the mid range between the two filters, A and B, and the best estimate of the place where the return fell. By choosing the proper clock rate it is possible to obtain a gated pulse train in which each pulse represents one cycle per second of Doppler shift.

Range Estimator

The purpose of the range estimator, shown in Fig. 11, is to make an accurate estimate of the time of occurence of the return, even though the video output which feeds the device has a very long time duration.

Before the range estimator will put out a range trigger, four different criteria must be met simultaneously: the input must exceed a certain preset amplitude threshold; a digital range-enable pulse must be positive; the slope of the input waveform must be negative; and the "centroid" of the input waveform must be nearly centered in a video delay-line, which is a means of avoiding gross errors in the estimate of the position of the range pulse at very low signal-to-noise ratios. At high signal-to-noise ratios this geometric criterion would not be necessary since it would be impossible to get a negative slop at any place other than the trailing edge of the target return.

Doppler Summarizer

The Doppler summarizer is a digital device which accepts inputs from the fine and coarse "greatest of" comparators and the Doppler interpolator and encodes and combines these to form a resultant digital Doppler word.

Figure 12, which shows the Doppler summarizer, is self explanatory.

IV. EXPERIMENTAL SYSTEM

Fig. 13 shows a block diagram of an experimental sequential Doppler processor which has been implemented using the Millstone Hill radar signal parameters in order to provide a means of testing it in actual target tracking operations.

The following is a description of the system:

The input is fed at 30 Mc from the radar receiver. Two channels are driven in parallel; one undelayed and one delayed by 2.5 milliseconds using an ultrasonic crystal delay-line. The undelayed channel is converted down to 200 kcps to feed the 13 filters of the coarse detector, and the delayed channel is converted (with a local oscillator frequency selected by the coarse detection equipment) down to a frequency which will place any target into a 5 kcps band centered at 200 kcps. The output of the delayed channel is then gated into a set of 21 narrow-band filters. If the output of any one of these filters exceeds a preset threshold, a legitimate echo is assumed to have occurred. The "greatest of" comparator then determines which of the filters has the highest peak response and controls the Doppler interpolator, which samples the amplitudes of the two filters adjacent (higher and lower frequencies) to the maximally-excited filter and converts this to a digital indication of where in the response of the center filter the return fell.

The results of the coarse, fine, and interpolation measurements are summed in the Doppler summarizer and then stored in a 16 bit accumulator.

The following is a discussion of some of the rationale behind the choice of the particular type, numbers, bandwidths, and spacings of the filters in the coarse and fine filter banks:

The first step was to choose the type, bandwidth, and spacing of the filters in the fine filter bank. For simplicity, single-tuned filters were chosen, and since the signal pulsewidth was two milliseconds, 200 cps filter bandwidths were used. A 250 cps filter spacing was chosen in order to provide a small total number of fine filters with an acceptable loss in signal midway between filters.

The second step was to choose the operational fine-filter threshold, and then to calculate the required IF input signal-to-noise ratio to yield a threshold crossing. In order to yield a high probability of detection, in excess of 95 percent, and a reasonably low false alarm rate, less than one per minute, an output signal-to-noise ratio of approximately 14db was required. A 200 cps single tuned filter in a 50 kilocycle IF bandwidth will yield a 14db output signal-to-noise ratio when the input is approximately minus 5db.

The third step was to determine the required medium-band filter pre-detection signal-to-noise gain at an input signal-to-noise ratio of -5db. An 8db signal-to-noise gain above IF was required to guarantee that the signal would present the detector with a plus 3db input signal-to-noise ratio, however, in order to be more conservative the requirement was set at a 9.5db pre-detection gain.

The fourth step was to choose the type of medium-band filter. Since the type is not critical once one gets above a single pole filter, a second order Butterworth filter was chosen.

Once the type of medium band filter was chosen the required band-

width and spacing could be determined. To achieve a 9.5db signal-to-noise improvement, a bandwidth of 5 kcps was required and in order to yield a low loss between filters a 4 kcps spacing was chosen.

The last step was to choose the total number of coarse and fine filters. Since the coarse filters had to cover the entire 50 kcps of Doppler with 4 kc spacing, a total of 13 filters were required. Since the fine filters only needed to cover a region of frequency slightly larger than the spacing between coarse filters only about 17 fine filters were required, but in order to reduce the stability requirements on the coarse-filter banks 21 fine filters were used in the experimental system.

The block diagram of Fig. 13 shows only a single IF input. The experimental system, however, accomodates two IF inputs, one for each of two orthogonal receiver polarizations.

The additional polarization is processed as follows:

A duplicate coarse filter bank and crystal delay-line is driven by the other polarization receiver. A comparison of the amplitudes out of the coarse filters from the two polarizations, controls the gating of the stored IF from the polarization with the greater signal.

The procedure is, in essence, to set up the coarse detection equipment in such a way that it provides information on the relative strengths of the signals in each polarization in addition to performing its basic functions.

For aid in testing the sequential processor, two binary to analog converters, one for the first 8 bits of Doppler and another for the next 8 bits, were included in the equipment to provide visual indications of Doppler on meters or analog recording devices.

The system can handle multiple targets (non-overlapping in range, or overlapping, but in the same coarse frequency region) and provides single pulse measurements, quantized to the nearest one foot per second, to signal to noise ratios as low as minus six db (at IF).

Figs. 14 and 15 show a front and rear view of the experimental system.

V. EXPERIMENTAL RESULTS

Tests were run during satellite tracking operations using the sequential processor and the Millstone filter bank in parallel, in order to obtain a comparison between the performance of the two systems. A digital computer accepted the data from both systems in real time and plotted the hit-by-hit output data. A detailed examination of these hit-by-hit data indicated that the sequential processor operated with

essentially the same probability of detection, and false-alarm rate as the full filter bank, in spite of the fact that the satellite returns were scintillating rather strongly and both systems experienced a wide range of input signal-to-noise ratios.

Figure 16 shows a segment of data taken from the sequential processor during the tracking of a satellite. The data was taken using a moving-pen recorder with one pen connected to a digital to analog converter fed by the eight most significant bits of digital Doppler output and the other pen, the eight least significant bits. Noise-induced jitter in the Doppler measurements can be seen modulating the bottom analog recording.

Computer plots of Doppler-report distributions for matched-filter output signal-to-noise ratios of 16db and 49db (IF signal-to-noise ratios of approximately minus 4db and plus 29db respectively) are shown in Fig. 17. The horizontal baseline of the photographs are 1,000 feet per second, representing two percent of the entire Doppler coverage band.

Fig. 18 shows a plot of the measured standard deviations of Doppler-report distributions as a function of $2E/N_o$ for the sequential processor. Although the experimental curve was plotted from 15 points, with each point calculated from a 5,000-sample distribution, the use of the Millstone computer in real time permitted the entire experiment to be run and the curve to be drawn in approximately one hour.

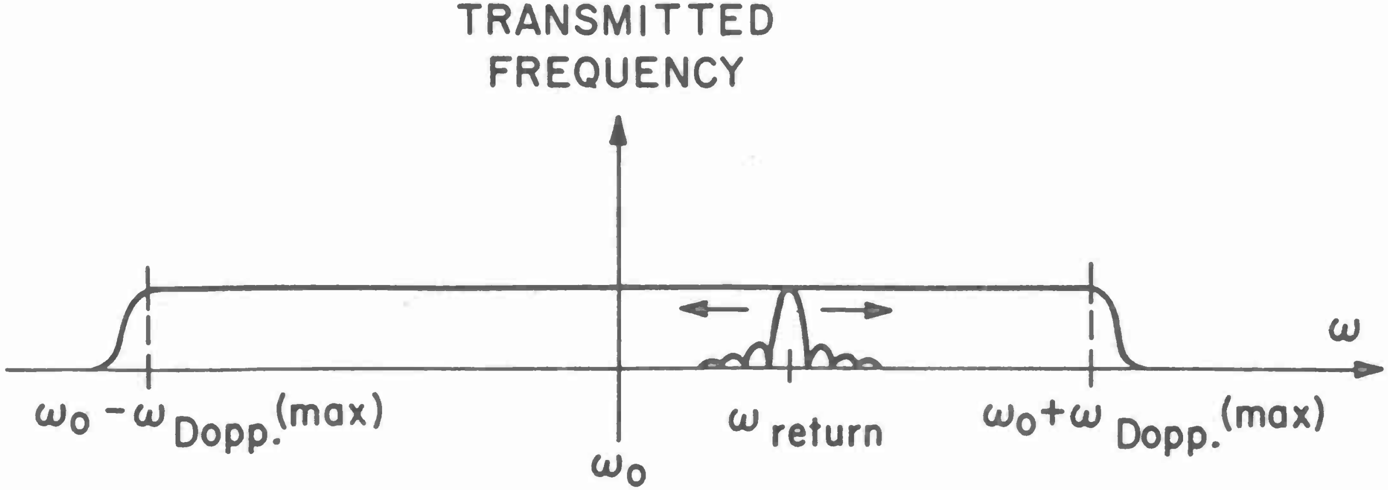
A plot of R. Manasse's formula for maximum theoretical Doppler accuracy[2] is shown for comparison with the experimental results. The discrepancy between the two curves has not as yet been fully explained and is presently under investigation.

VI. CONCLUDING REMARKS

The experimental prototype system succeeded in simulating a set of four hundred filters with only forty-seven filters, and operated with essentially no sacrifice in performance when compared to the many-filter method of detection. The techniques should be applicable to an extrapolated version of this system for the simulation of a much larger filter bank. A sequential processor is presently being designed to process 10 millisecond simple, rectangular pulses (± 100 cps $\frac{\sin x}{x}$ first null) in a Doppler band 1.5 mcps wide; a problem which, with the use of a conventional narrow-band comb set, would require 30,000 filters for its solution.

FOOTNOTES

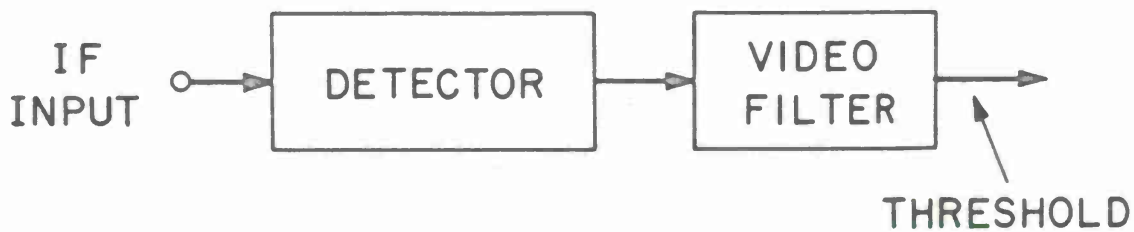
(1) Lincoln Laboratory tracking-radar field site, Westford, Mass.
(2) R. Manasse, "Summary of Maximum Theoretical Accuracy of Radar Measurements" Mitre Corp. Technical Series Report No. 2



PROBLEM:
DETECTION OF NARROW - BAND RADAR RETURN
IN NOISY, WIDE - DOPPLER - BAND ENVIRONMENT

FIG. 1

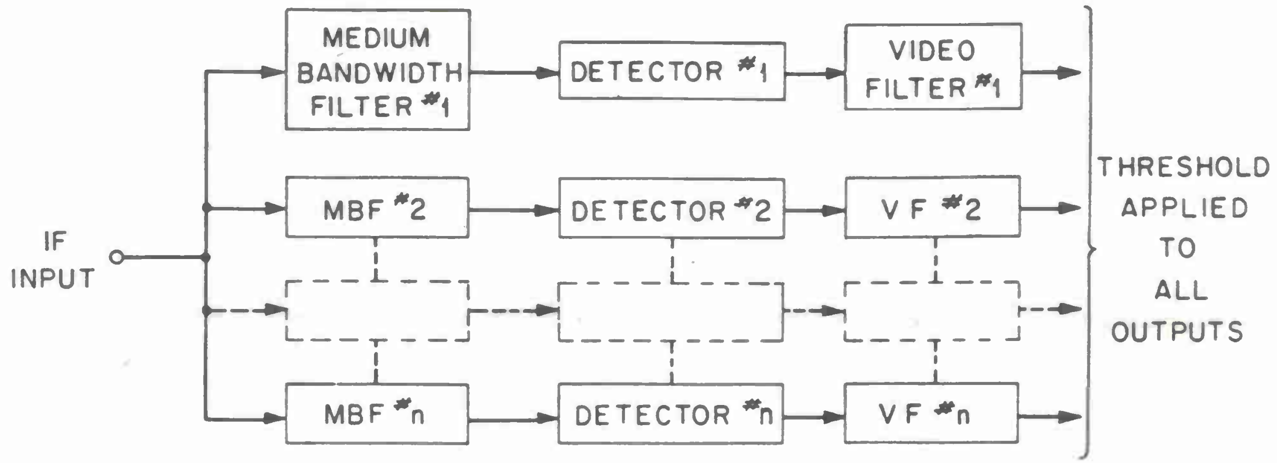
A-12987-5



SIMPLE METHOD FOR DETECTION;
GOOD AT HIGH S/N

FIG. 2

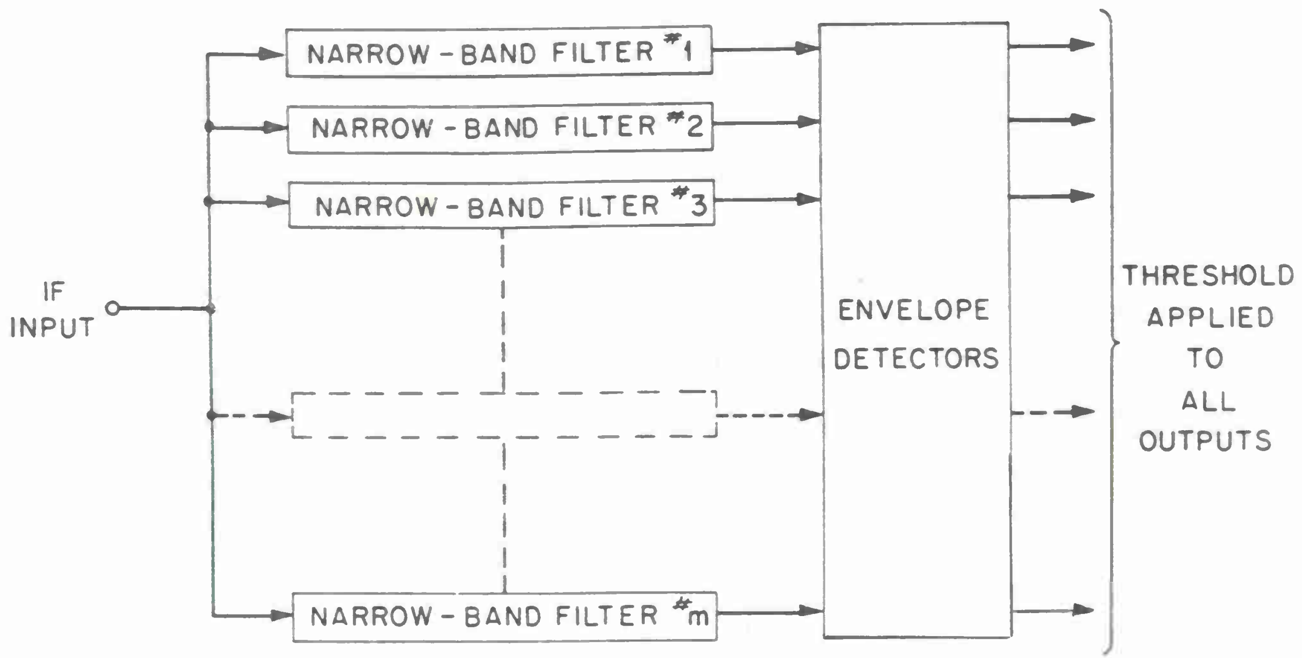
A-12987-4



METHOD FOR DETECTION GOOD AT MEDIUM S/N

FIG. 3

B-12987-2



METHOD FOR DETECTION GOOD AT LOW, MEDIUM AND HIGH S/N

FIG. 4

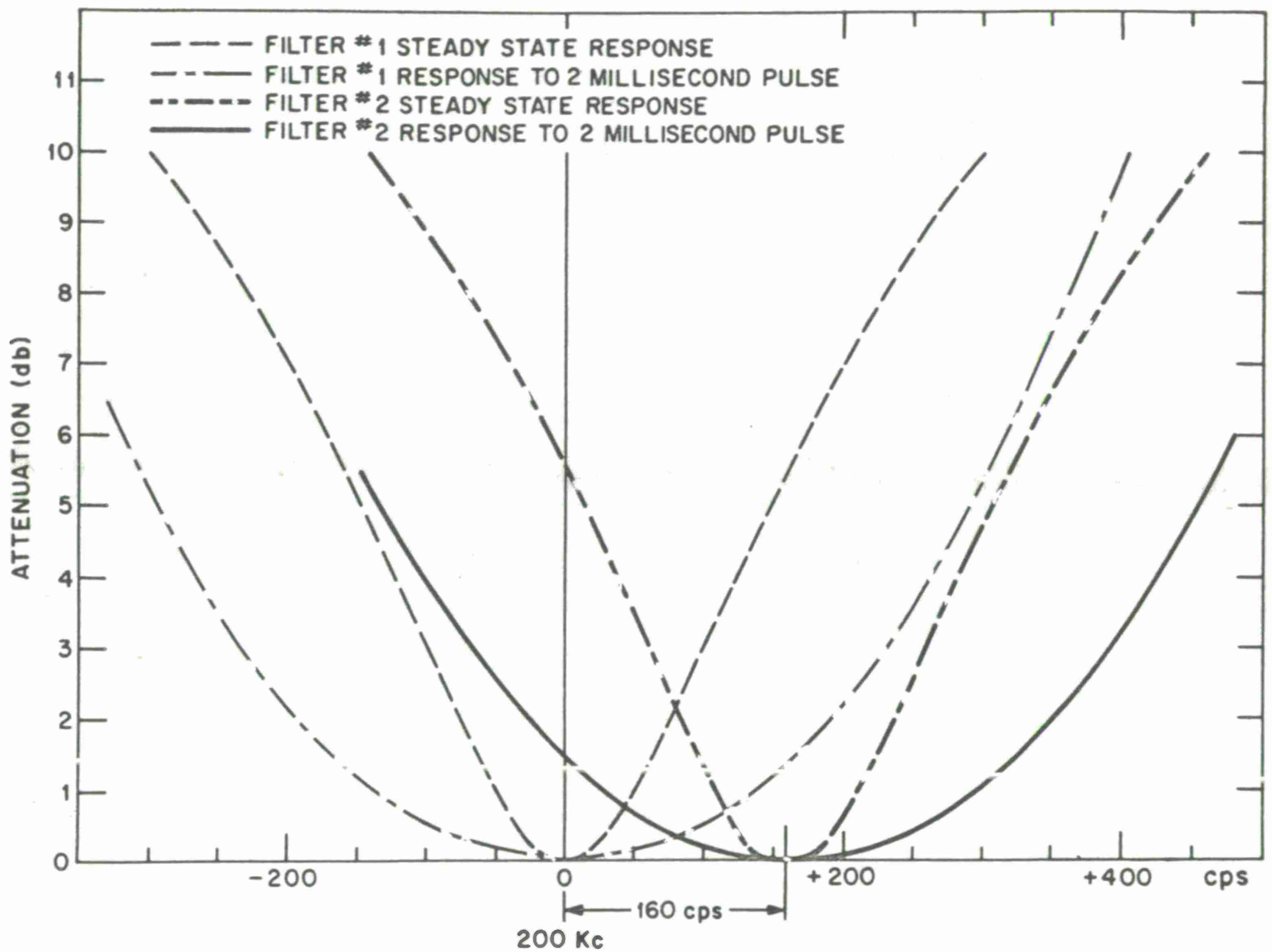
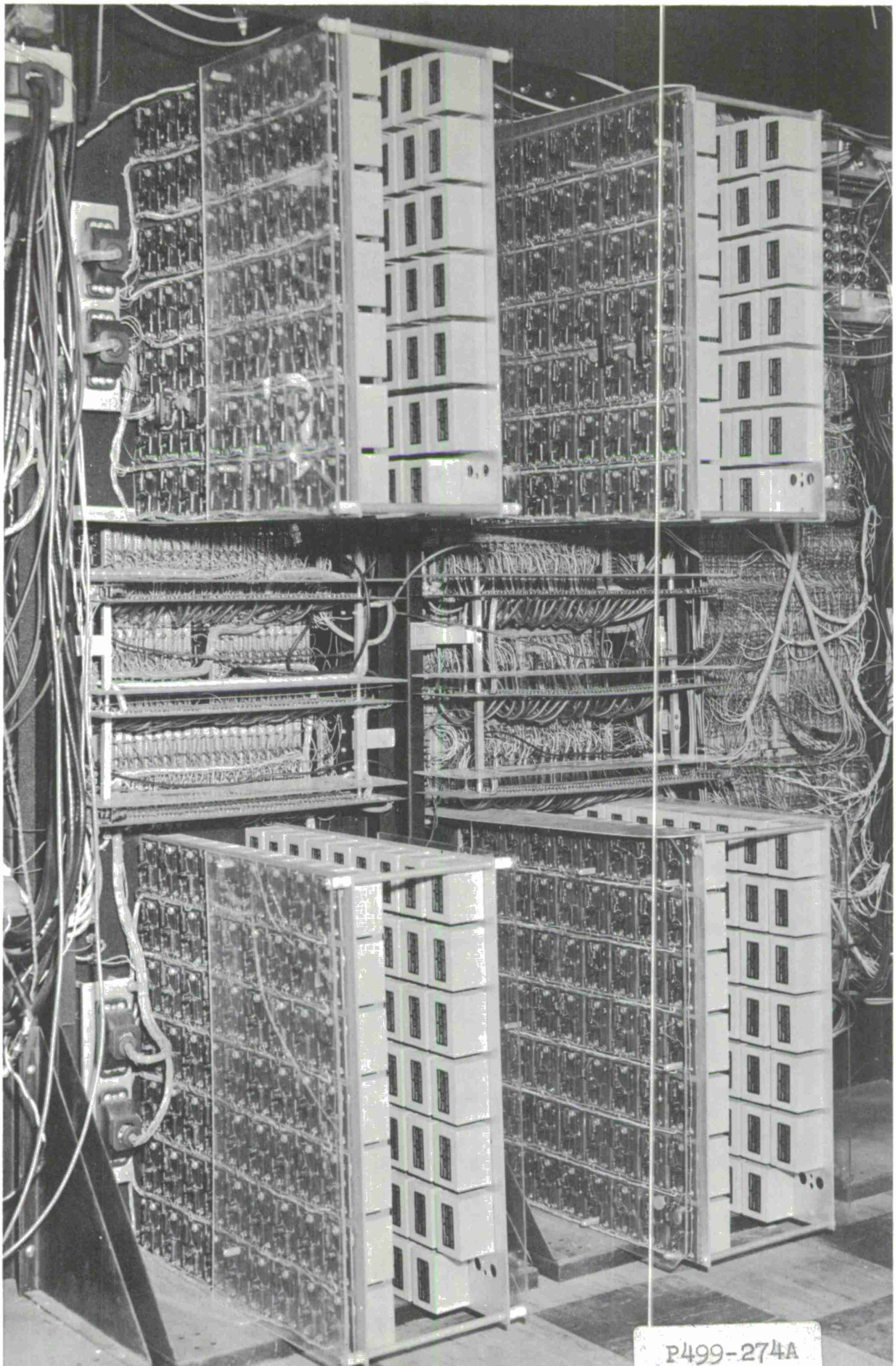
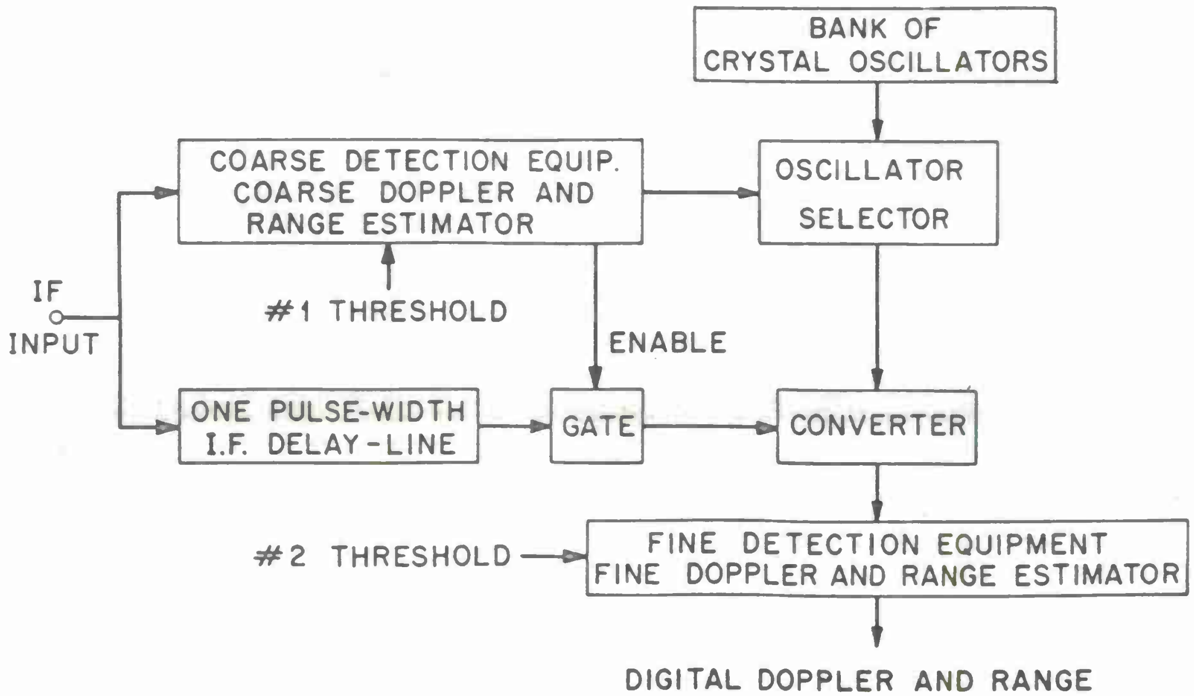


FIG. 5 STEADY STATE AND TRANSIENT SELECTIVITY CHARACTERISTICS OF TWO ADJACENT DOPPLER FILTERS.



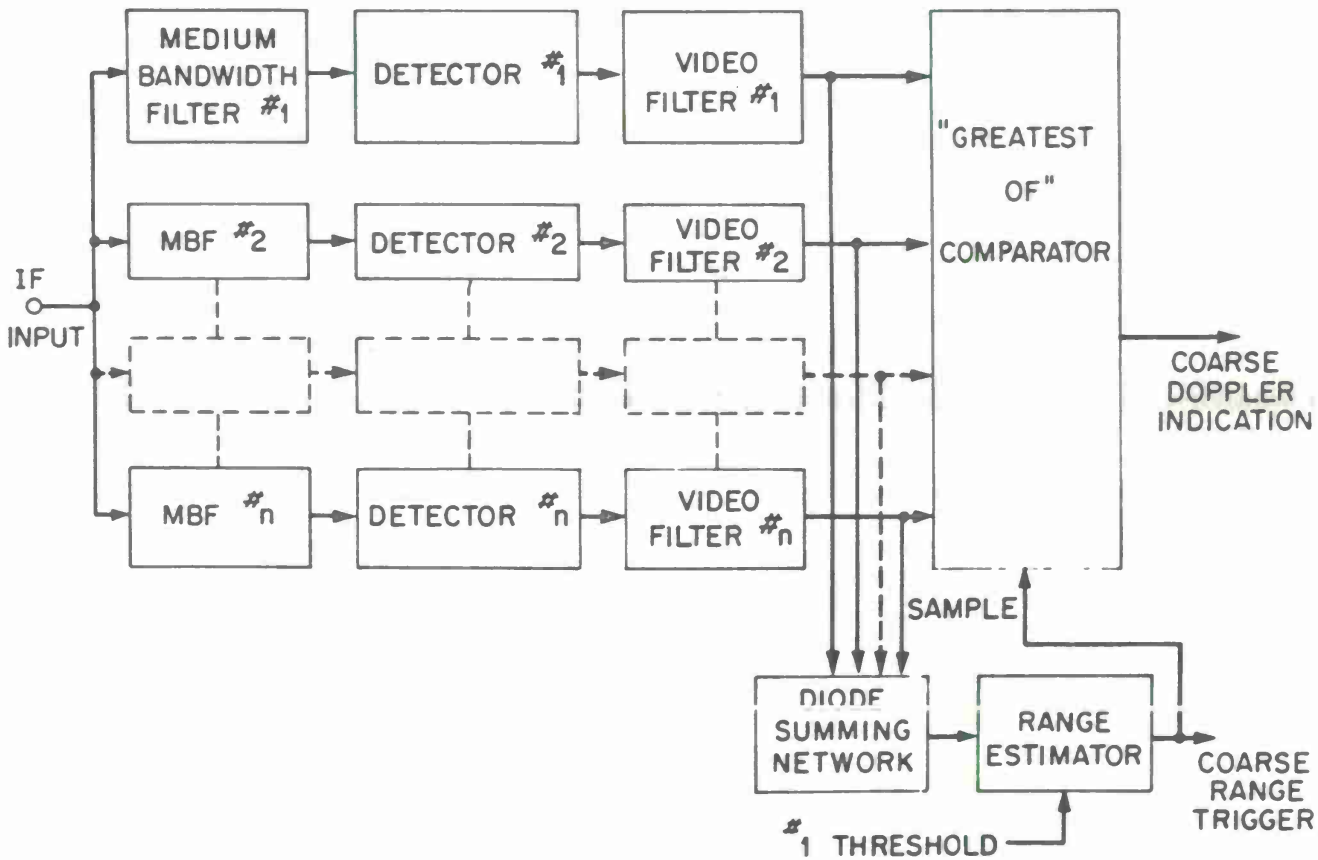
SECTION OF MILLSTONE FILTER BANK
FIG. 6



SEQUENTIAL DETECTION AND PROCESSING SYSTEM

FIG. 7

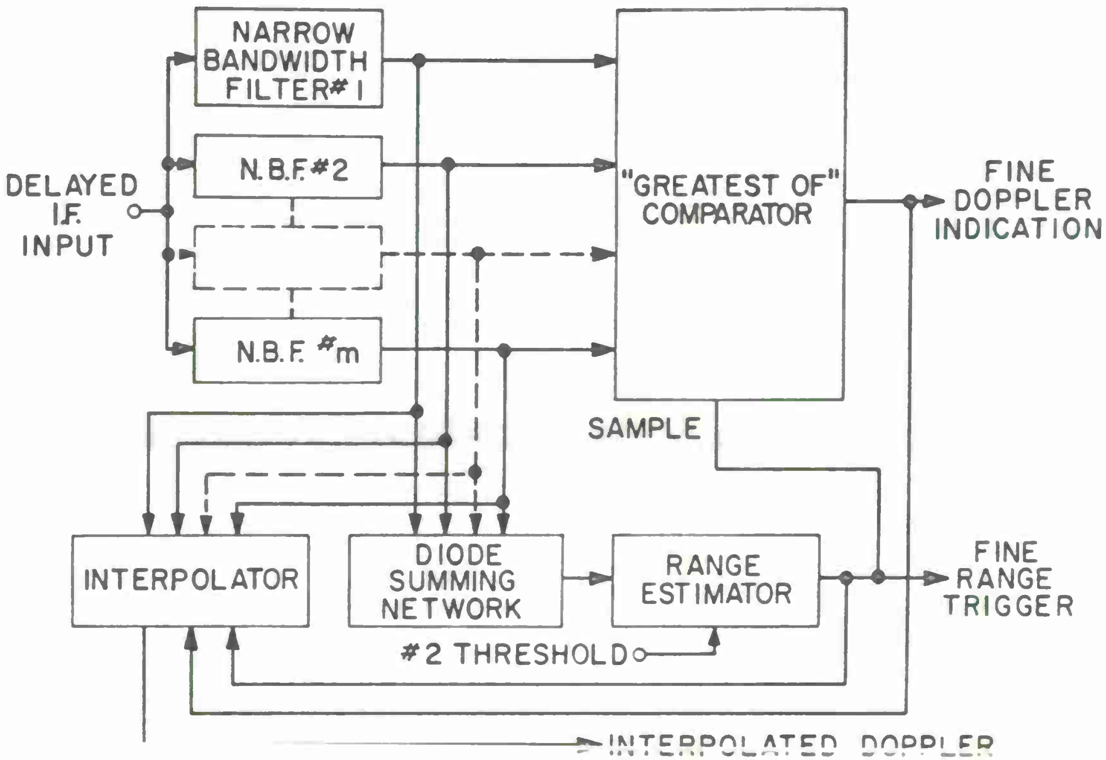
B-12987-3



COARSE DETECTION EQUIPMENT, COURSE DOPPLER AND RANGE ESTIMATOR

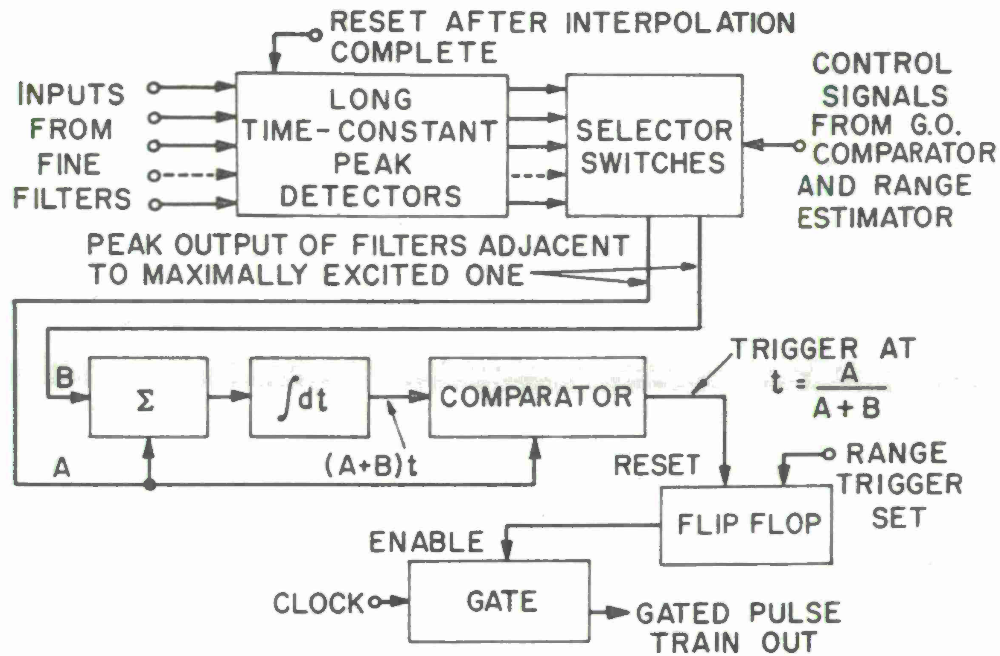
FIG. 8

B-12987-8



FINE DETECTION EQUIPMENT,
FINE DOPPLER AND RANGE ESTIMATOR
FIG. 9

B-12987-6



DOPPLER INTERPOLATOR
FIG. 10

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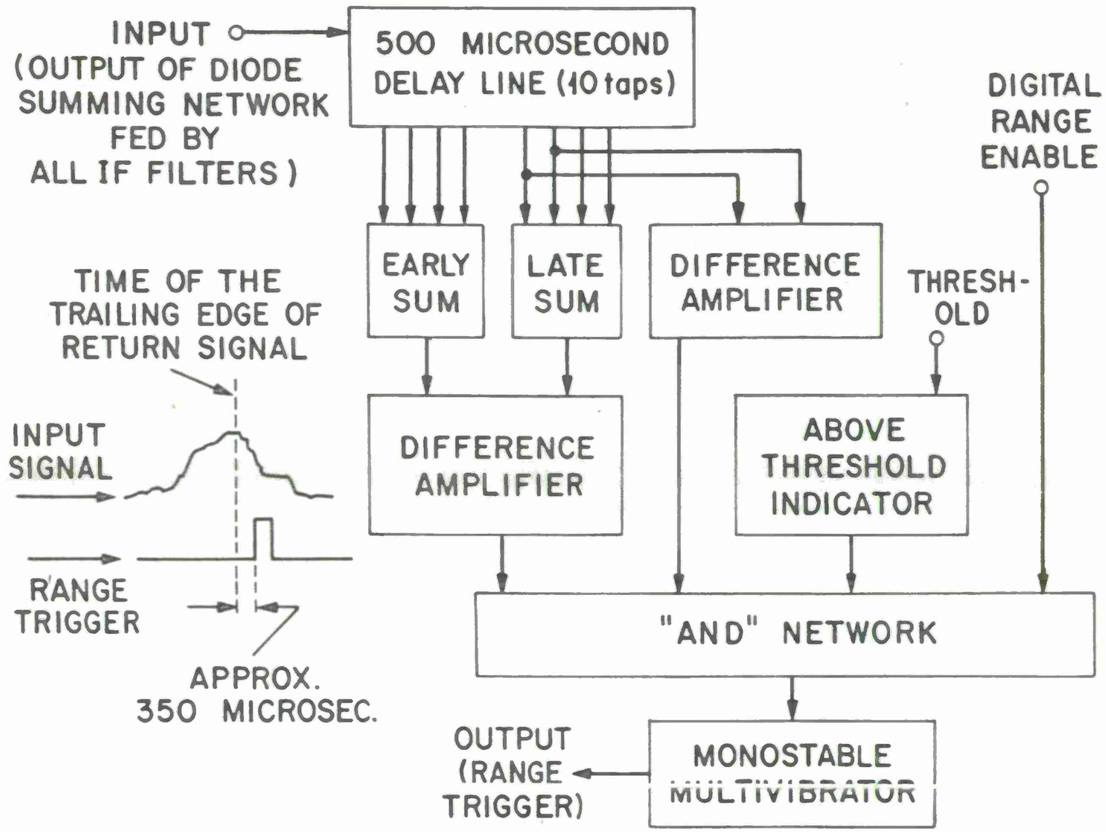
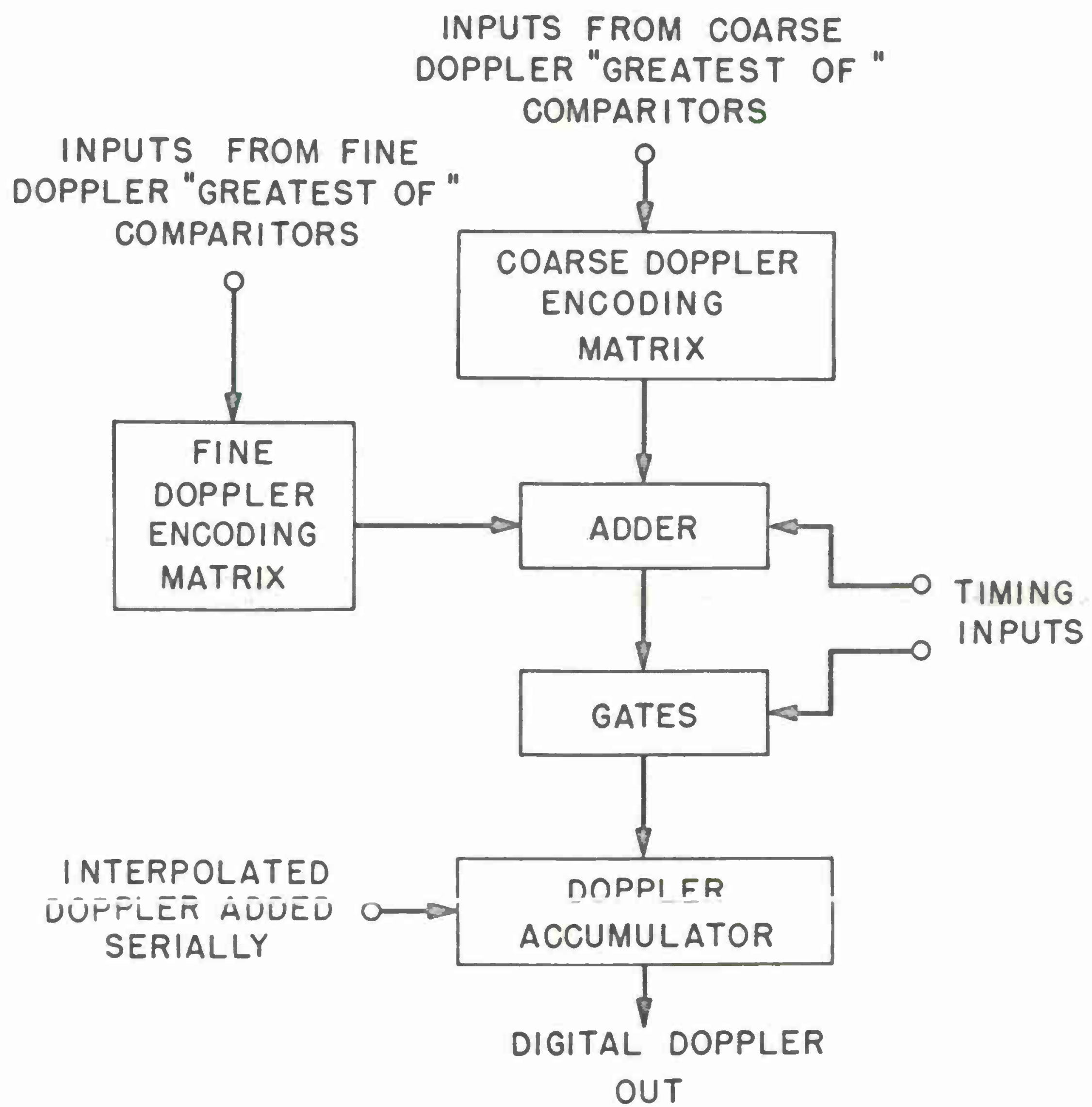


RANGE-PULSE FORMER (FOR TWO-MILLISECOND PULSE)

FIG. 11.

B-12987-11



DOPPLER SUMMARIZER

FIG. 12

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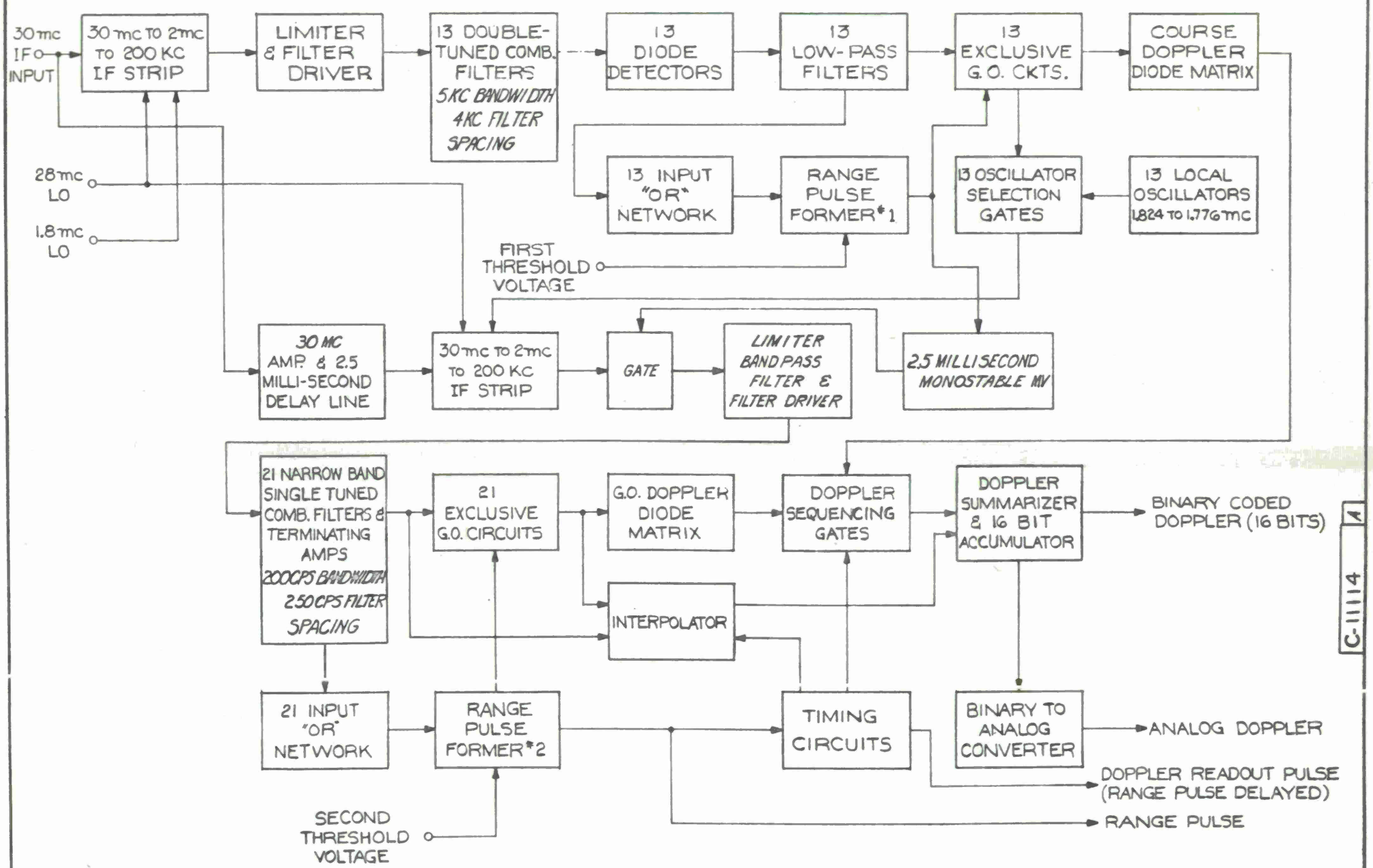
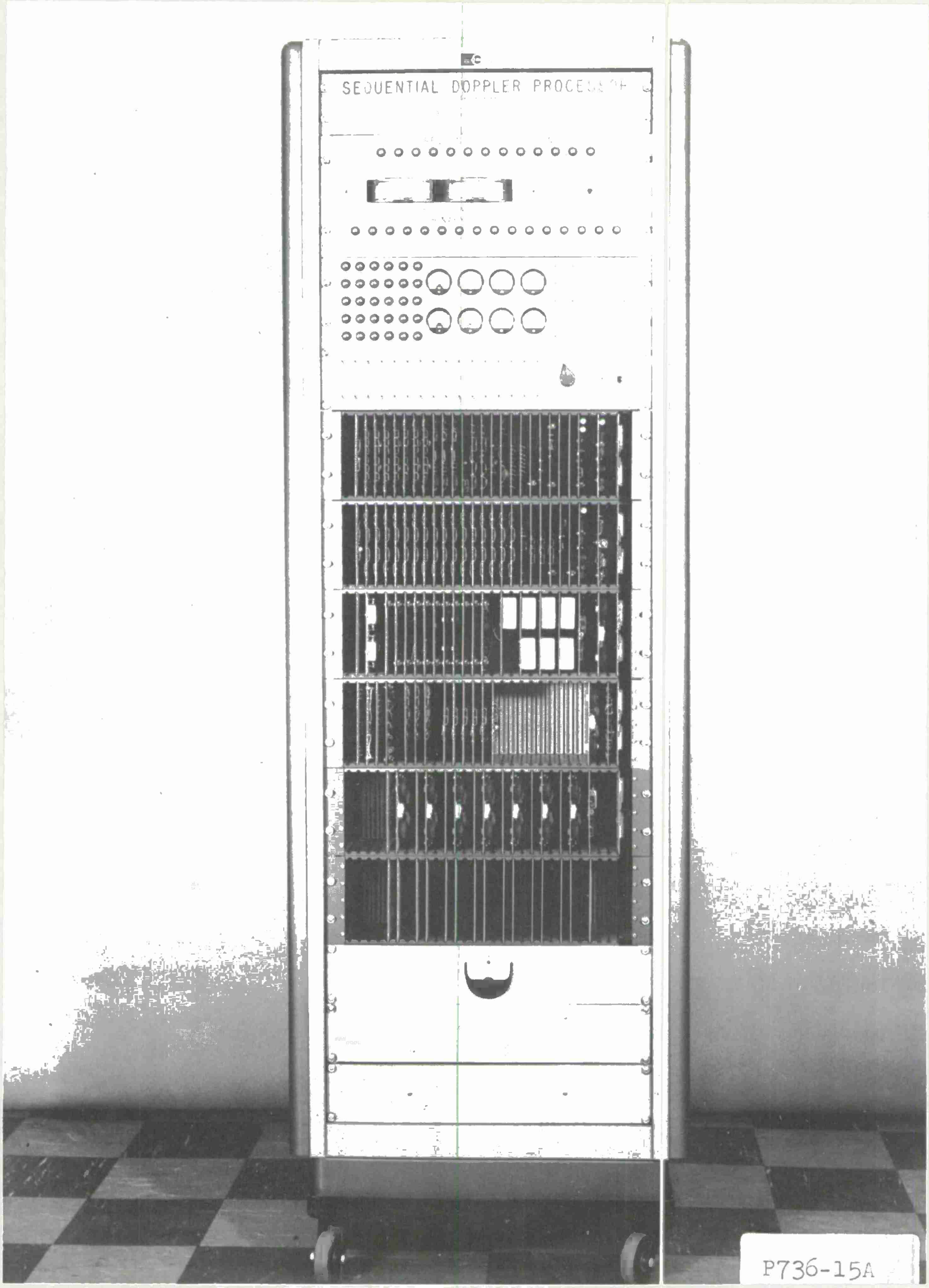
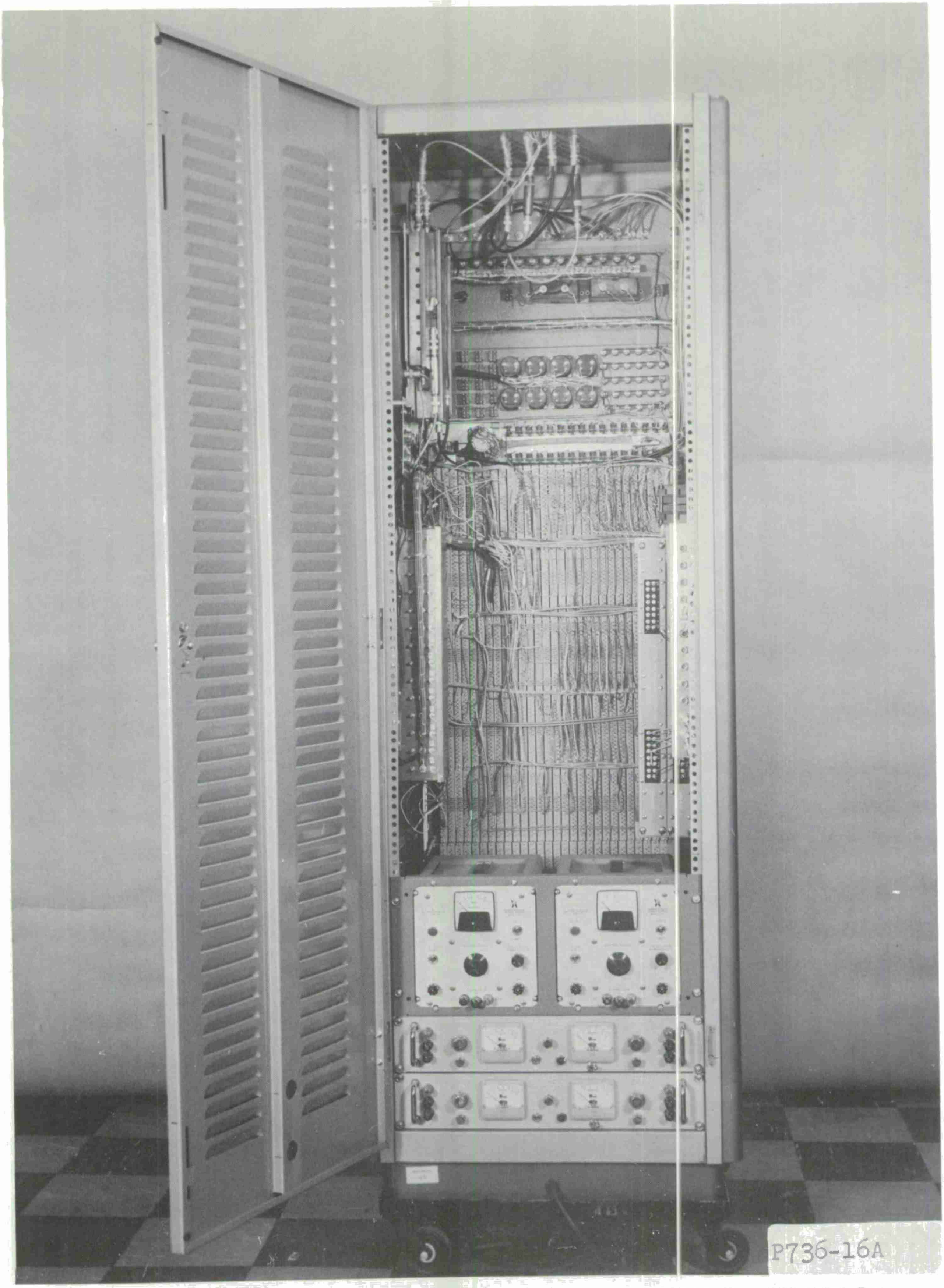


NOTE:
ONLY ONE POLARIZATION SHOWN

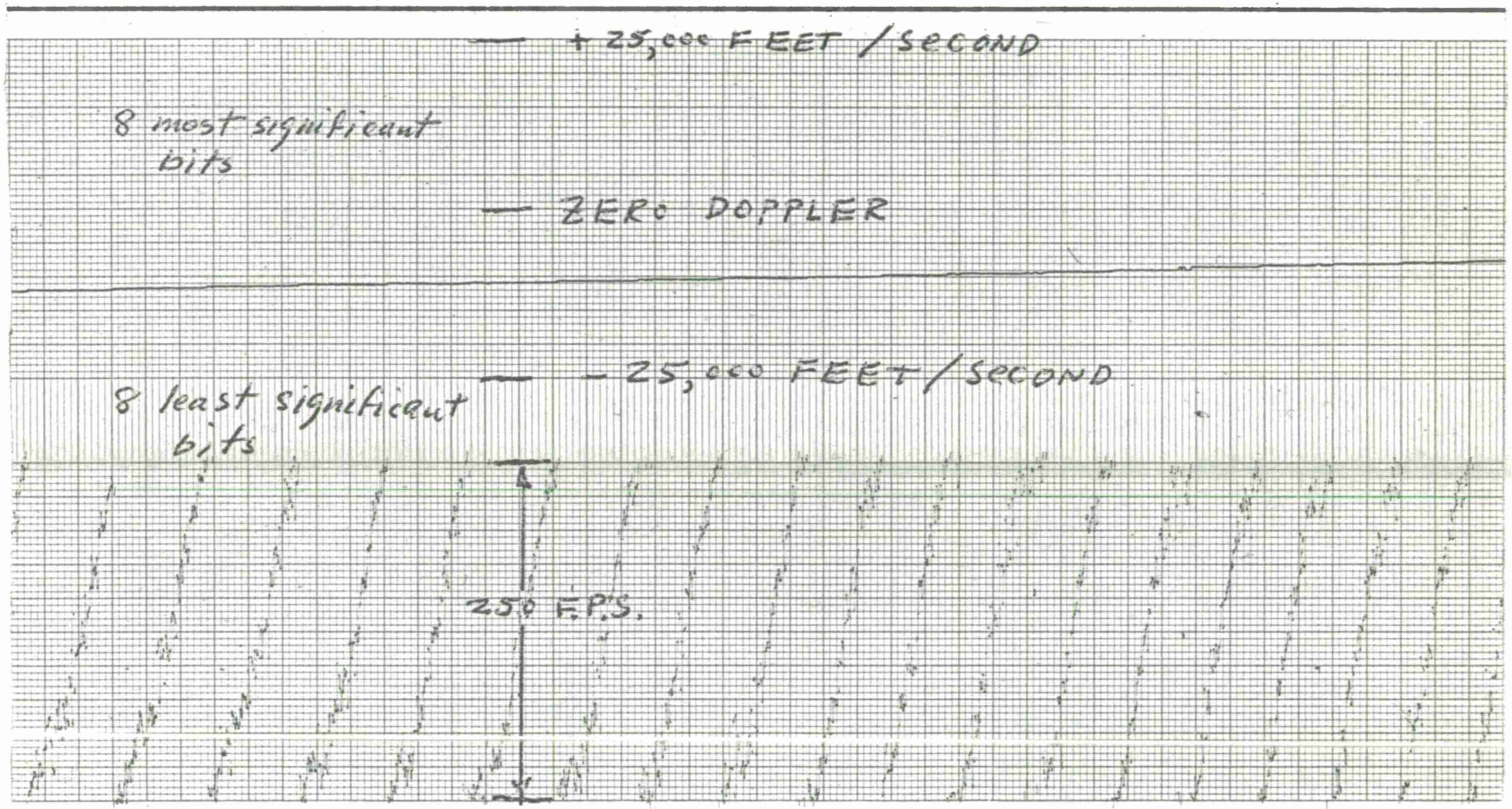
FIG. 13 EXPERIMENTAL SEQUENTIAL PROCESSOR FOR TWO - MILLISECOND PULSE AND FIFTY KILOCYCLE DOPPLER BAND



FRONT VIEW OF EXPERIMENTAL SEQUENTIAL PROCESSOR
FIG. 14

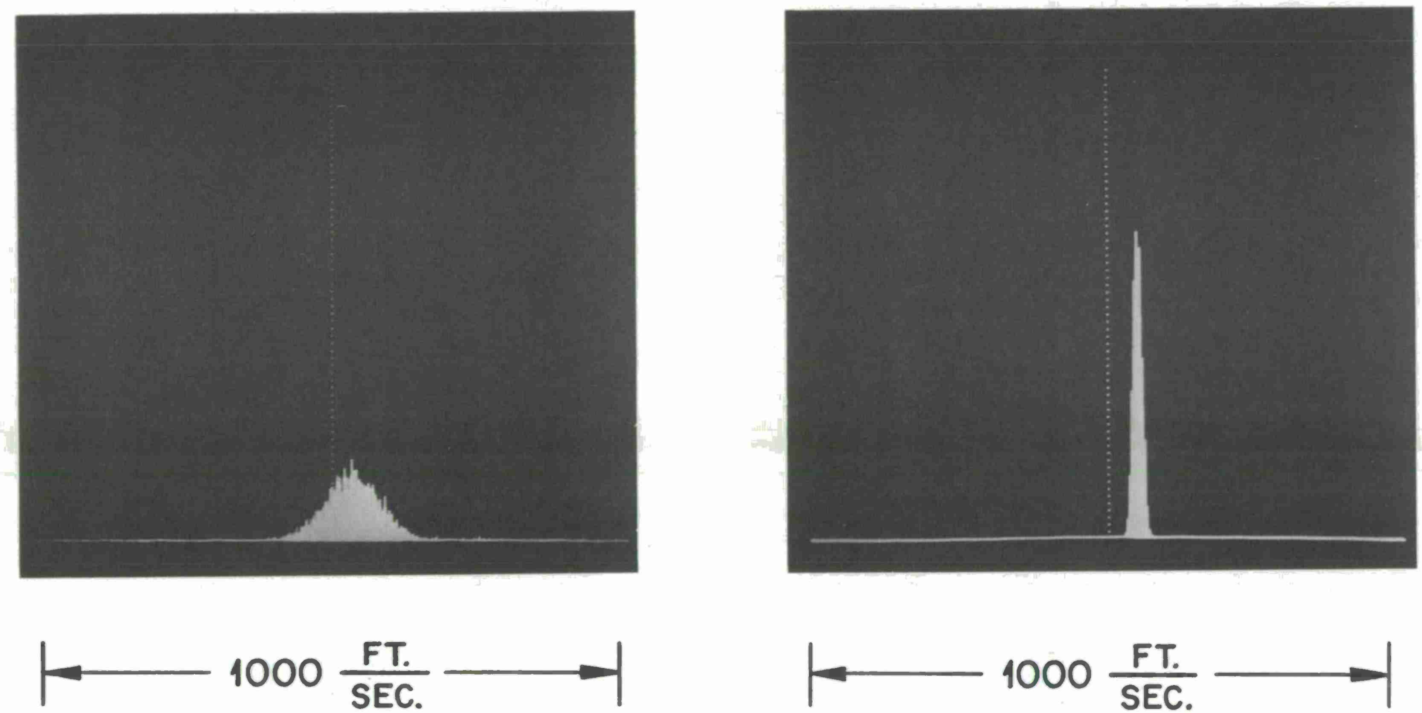


REAR VIEW OF EXPERIMENTAL SEQUENTIAL
PROCESSOR
FIG. 15



ANALOG CONVERSIONS OF DIGITAL DOPPLER
REPORTS OBTAINED WHILE TRACKING A SATELLITE
FIG. 16

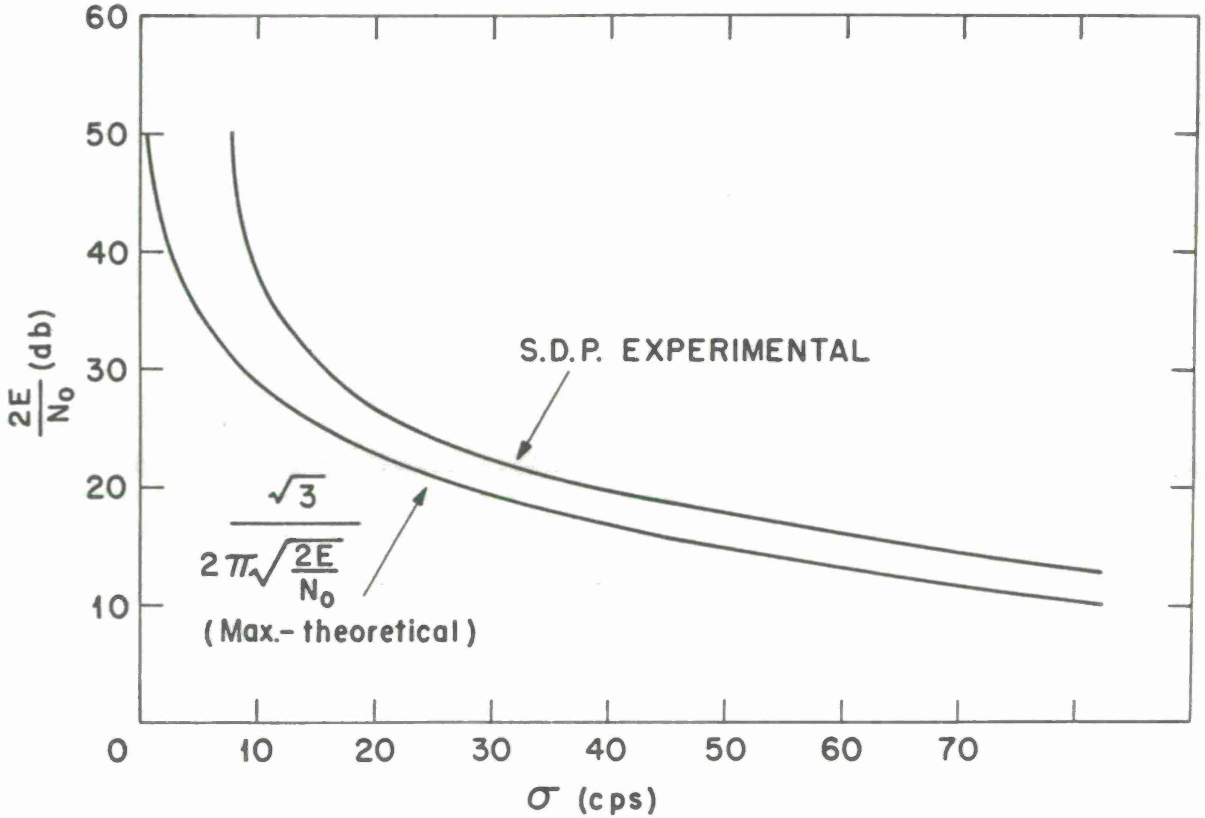
C41-101



MEASURED DISTRIBUTION'S OF DOPPLER REPORTS FOR SIGNAL TO NOISE RATIOS OF 16db (left) AND 49db (right)

FIG. 17

C41-102



STANDARD DEVIATION OF DOPPLER-REPORT DISTRIBUTION vs. $\frac{2E}{N_o}$

FIG. 18

B-12987-10

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

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13. ABSTRACT

This report describes a system which permits a substantial reduction in the amount of equipment required for the detection of narrow-band radar returns which may fall into any part of a wide, noisy Doppler band. The system utilizes a two-step process; the first providing a coarse, high-false-alarm indication of range and Doppler, and the second providing high quality detection and parameter estimation. The basic principles are discussed, followed by a description of an experimental prototype system. Experimental results are presented.

14. KEY WORDS

detectors
detection
radar detection

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